

Homogeneity tests on neutron shield concrete

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In recent years, neutrons have been studied for application in fields such as material analysis and boron neutron capture therapy. To create a compact shield for these facilities, a neutron shield concrete is developed. Verifying the homogeneity of the concrete is important to ensure adequate shielding performance. In this research, neutron radiography images of the concrete are taken using the Thermal Neutron Radiography Facility (TNRF) of the JRR-3 research reactor, and the transmission ratio of the thermal neutrons were estimated. The results showed that the transmission ratio of the concrete was almost the same at each depth.

Keywords: Neutron, Neutron radiography, Shielding, Concrete

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I. INTRODUCTION

In recent years, neutrons have been studied for application in various fields, such as material analysis and boron neutron capture therapy. To create a compact shield for such facilities, a neutron shield concrete that has the same mechanical strength as ordinary concrete has been developed [1]. This concrete contains about 15 wt% of hydrogen and about 3 wt% of B₂O₃.

It is important to verify the homogeneity of the boron and hydrogen content in the concrete to ensure adequate shielding performance. Therefore, neutron radiography images of the concrete were taken using the Thermal Neutron Radiography Facility (TNRF) of the JRR-3M research reactor and the transmission ratio of the thermal neutrons was estimated.

Visualization of water penetration into concrete through cracks using neutron radiography was reported recently [2], but no application of visualization of homogeneity exists.

II. NEUTRON SHIELD CONCRETE

Neutron shield concrete uses colemanite and peridotite rocks as aggregates. Colemanite is a natural mineral that is rich in boron in the form of B₂O₃. Peridotite is a natural mineral that is rich in hydrogen atoms in the form of H₂O. These aggregate materials, together with ordinary Portland cement, form concrete. Colemanite was used for 10 wt% of the concrete composition to improve the shielding performance and production of the concrete. The density of the neutron shield concrete is the same as that of ordinary concrete. Thus, the neutron shield concrete includes B₂O₃, which has a large capture cross section for thermal neutrons, and abundant H₂O, which slows down neutrons around 2 MeV via elastic scattering. This shield concrete also contains more iron in the form of Fe₂O₃ than ordinary concrete, which slows down high-energy neutrons via inelastic scatterings. These effects provide the concrete with unique shielding performance. Table 1

shows the element analysis for the neutron shield concrete and the ordinary concrete, both of them have the same average density of 2.2 g/cm³.

Table 1. Results of density and elemental analysis.

Neutron shield concrete (wt%)				
SiO ₂	H ₂ O	MgO	MnO	Al ₂ O ₃
33.1	14.8	29.1	0.09	1.54
CaO	SO ₃	Cl	Cs	Na ₂ O
11	0.38	0.016	<0.01	0.05
TiO ₂	B ₂ O ₃	P ₂ O ₅	Eu	CoO
0.07	2.61	0.11	<0.01	<0.01
Fe ₂ O ₃	K ₂ O	Ig-loss	Density	
6.23	0.06	13.6	2.2 g/cm ³	
Ordinary concrete (wt%)				
SiO ₂	H ₂ O	MgO	MnO	Al ₂ O ₃
57.7	6.04	1.31	0.08	10.5
CaO	Cs	Na ₂ O	K ₂ O	TiO ₂
14.5	<0.01	2.29	0.86	0.39
Fe ₂ O ₃	Eu	Co	Density	
3.47	<0.01	<0.01	2.2 g/cm ³	

III. NEUTRON RADIOGRAPHY

Neutron radiography, a non-destructive imaging technique that uses thermal neutrons, is a powerful tool for inspecting materials. The difference between the neutron and X-ray imaging techniques is that X-ray attenuation depends on atomic numbers, whereas neutron attenuation is different for each nucleus. Fig. 1 shows the attenuation coefficient for thermal neutrons [3].

When the neutron beam irradiates a sample, the camera that is located behind the sample takes a picture with black and white contrast. Substantial attenuation of thermal neutrons in elements, such as hydrogen and boron, will cause these neutrons to appear shadowed in the radiographic image. Therefore, while water is not visible in X-ray imaging, it is clearly visible in neutron radiographs because of its high hydrogen content. As shown in Fig. 1, hydrogen, lithium, boron, etc.

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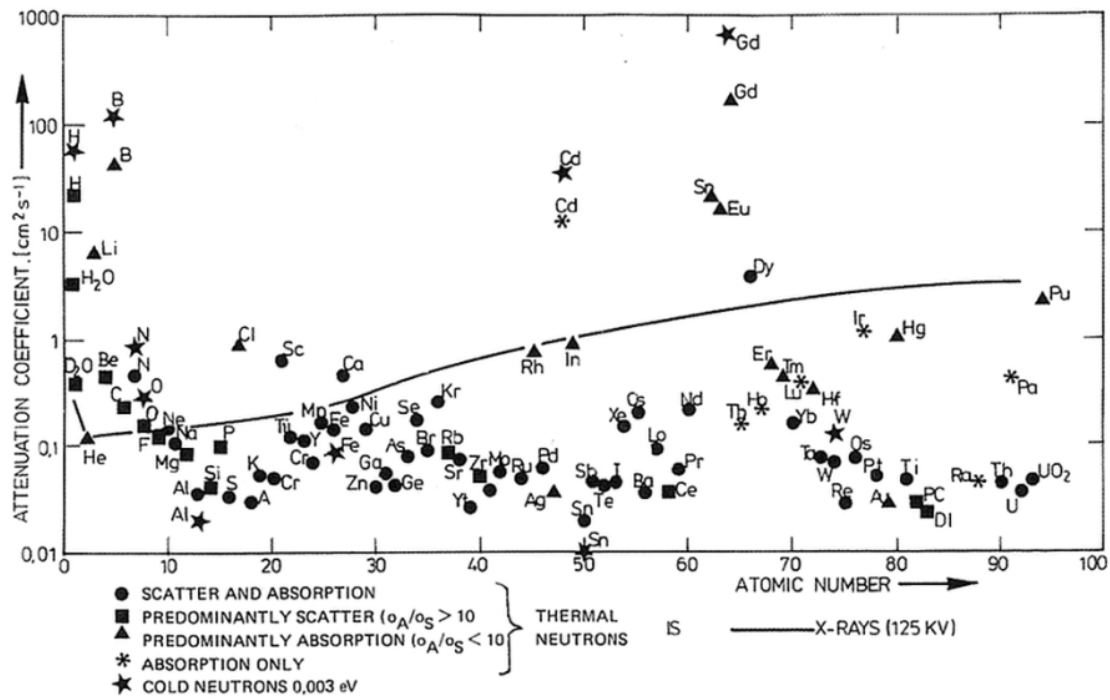


Fig. 1. Attenuation coefficient of each element for thermal neutrons.

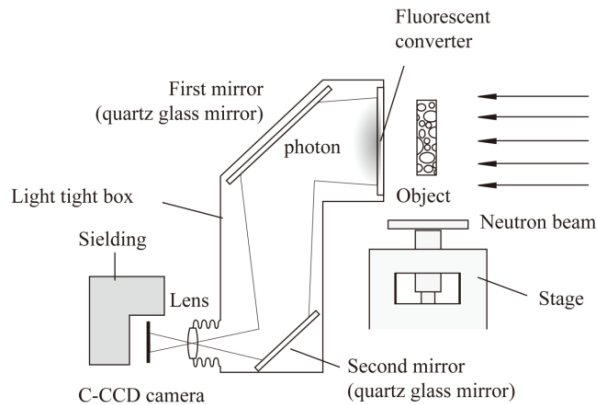


Fig. 2. Experimental system of the TNRF.

have a large attenuation ratio, whereas silicon, calcium, oxygen, aluminum, etc. have a small attenuation ratio.

A thermal neutron beam can be found in a research reactor. The TNRF is installed at the JRR-3M research reactor of the Japan Atomic Energy Agency. Table 2 shows the specifications of the TNRF, and Fig. 2 shows its experimental system. In Fig. 2, the thermal neutron beam comes from the JRR-3M and impacts the object. The fluorescent converter is a combination of a scintillator and Gd or ^6Li . When a thermal neutron is captured by Gd or ^6Li , the scintillator fluoresces. The fluorescence is scattered by the mirror, and then a photograph or video image is taken with the cold CCD camera.

Table 2. Specifications of the TNRF

Thermal neutron flux	$1.2 \times 10^8 (n/cm^2/s)$
Irradiation area	255 mmW \times 305 mmH
Resolution of cold-CCD	100 $\mu\text{m}/\text{pixel}$
Fluorescent converter	Li-loaded ZnS scintillator

IV. EXPERIMENT

Ordinary concrete and neutron shield concrete were used as experimental samples. As shown in Fig. 3, 20 mm thick slices were obtained from a concrete sample of cylinder with $\phi 100$ mm (diameter), starting at the surface and proceeding to greater depths of the core sample, and used for the experiment.

Each sample of sliced concrete was set in front of the fluorescent converter. The experimental setup is shown in Fig. 4.

V. RESULTS AND DISCUSSION

The intensity of the neutron beam that passes through the concrete sample is described by the following equation[4]:

$$I = I_0 \exp\left(-\sum_t T\right), \quad (1)$$

where \sum is the macroscopic cross section, t is the sample thickness, I is the intensity of the neutron beam that passes through the sample, and I_0 is the incident intensity of the neutron beam.

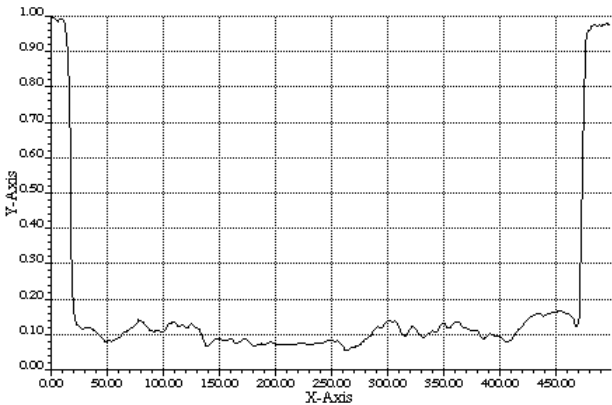
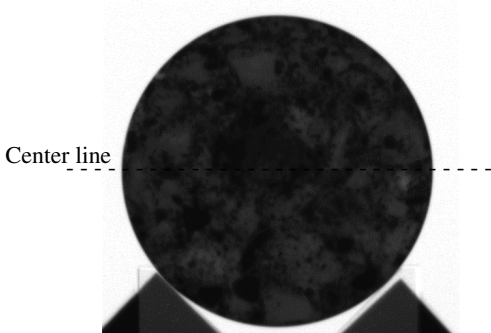


Fig. 3. (Color online) Concrete sample.

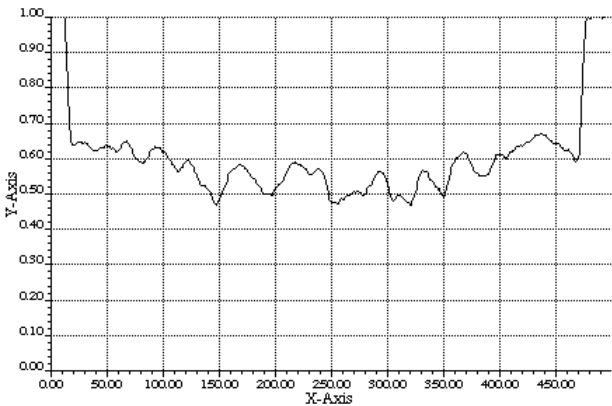
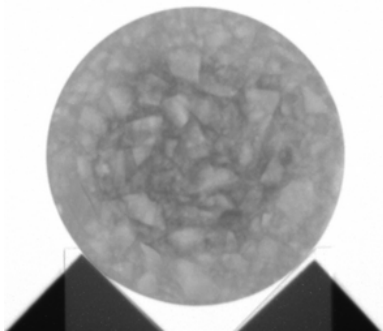


Fig. 4. (Color online) Experimental setup.

(1) Surface
a) Neutron Shield Concrete



b) Ordinary Concrete



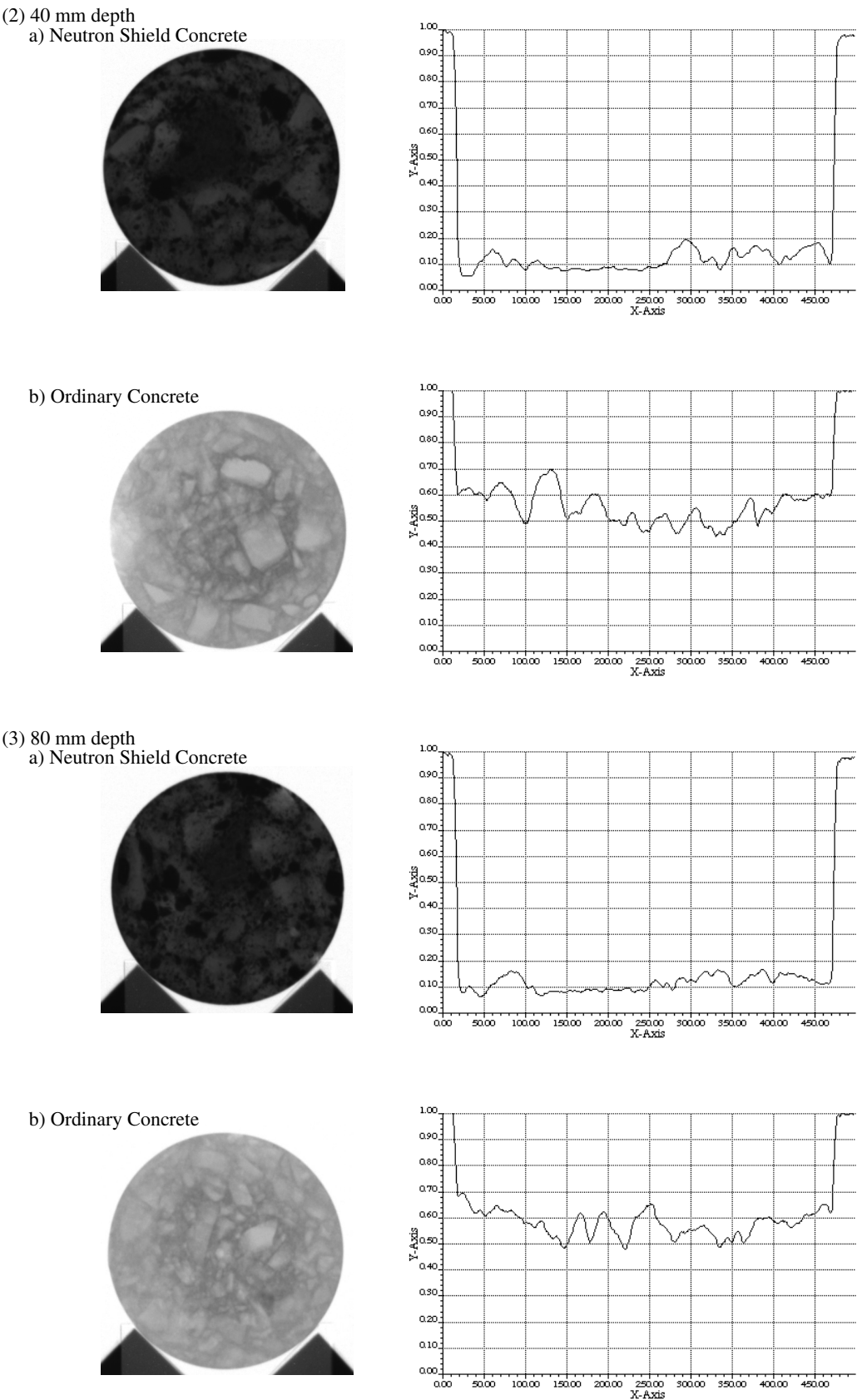


Fig. 5. Neutron radiography images of transmission ratio at the center line.

The neutron radiography images and the respective transmission ratio of each, measured at a line through their centers, are shown in Fig. 5. In these images, the intensity of the neutrons appears as contrasting black and white. Thus, the intensity can be read as digital bit data. These images were produced from image processing software through digital bit analysis. A transmission ratio of 1.00 (white) means no shielding, while a ratio of 0.00 (black) means complete shielding.

As shown in Fig. 5, the transmission ratio of each concrete sample was almost the same for each depth. No large frequency appears in the graph, which indicates good homogeneity at the center line and, thus, no breaks in the shielding. The transmission ratio of the neutron shield concrete is almost half that of the ordinary concrete, which indicates that

the shielding performance is almost twice as good as that of ordinary concrete.

VI. CONCLUSION

Tests on the homogeneity of neutron shield concrete were performed using neutron radiography. The results showed that the transmission ratio of the concrete was almost the same at each depth. Thus, neutron radiography imaging is useful for this type of investigation.

The result of this study is still qualitative. Therefore, the future plan is to develop this study to perform quantitative analysis and accurate estimation.

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